REPORT No. 147

STANDARD ATMOSPHERE

By WILLIS RAY GREGG
United States Weather Bureau

REPORT No. 147.

STANDARD ATMOSPHERE.

By Willis Ray Gregg.

SUMMARY.

Upon the recommendation of the subcommittee on aerodynamics at its meeting of December 17, 1921, the executive committee of the National Advisory Committee for Aeronautics adopted for performance testing Toussaint's formula of temperature decrease with height for obtaining air density at different altitudes.

The National Advisory Committee for Aeronautics further requested the United States Weather Bureau to prepare a technical report[1] covering the actual observations on the variation of temperature, pressure, and density of the atmosphere for summer, winter, and the year.

It has been shown from observations over a long period that up to 10 or 12 kilometers the mean variation of temperature with altitude in the United States is expressed very closely by Toussaint's formula

$$t = 15 - 0.0065Z$$

where t is the temperature in degrees centigrade and Z the altitude in meters. From 12 to 20 kilometers the temperature is approximately constant at $-55°$ C. as shown by Table 1 ($-67°$ F. in English units, Table 4) in the following report which gives the mean observed values of pressure and temperature at various altitudes for the United States (latitude 40°) for summer, winter, and mean annual conditions. The values calculated from Toussaint's formula are given in Table 3 (Table 5 in English units) and are in substantial agreement with the observed mean annual values of Tables 1 and 4. The subcommittee on aerodynamics, therefore, recommended for the sake of uniform practice in different countries that Toussaint's formula be adopted in determining the standard atmosphere up to 10 kilometers (33,000 feet) as given in Tables 3 and 5. For altitudes higher than 10 kilometers (33,000 feet), values of pressure and temperature should be taken from Table 1 or Table 4. In many cases where it is desired to use values which more closely approximate actual conditions than those obtained by Toussaint's formula, the approximate values (summer or winter) should be taken from Table 1 or Table 4.

INTRODUCTION.

With the advance of aeronautics and the science of artillery, engineers and other specialists in these fields have come to require a specific knowledge of the varying states of the atmosphere from the ground up to very great heights. This has led to the introduction of a conventional term commonly known as the "standard atmosphere," which pretends to specify the normal or average condition. As is well known, the "standard atmosphere" is never found; that is to say, at no time or place do "standard" or average conditions of all of the meteorological elements at all altitudes simultaneously occur. Nevertheless it is proper, and in certain fields (especially those of aviation and ordnance) it is necessary, to adopt so-called "standard" values, and it is desirable to have these represent as closely as possible true mean values in

[1] This report is in part based upon a paper entitled "An Aerological Survey of the United States," published by the Weather Bureau, in which is presented a discussion, with tables and figures, of the free-air conditions of pressure, temperature, humidity, density, and wind in this country, as determined from a large number of observations by means of kites and balloons.

order that corrections due to departures from these means may be comparatively small in most cases. Hence, the adoption of an "isothermal atmosphere," proposed by some investigators, although a desirable simplification in some respects, is inadvisable because of the large corrections that would have to be applied at practically all altitudes. Although a knowledge of temperature may not be vital in aerodynamic tests, it certainly is important when the thermodynamic or power production phase is considered. Moreover, in the design, construction and use of altimeters a knowledge of the altitude-pressure relation is essential, and this relation varies decidedly with temperature. What is needed, then, in defining the "standard atmosphere," is a series of values of pressure, temperature, and density, at different altitudes, these values to represent as closely as possible actual average conditions. If tables or curves were prepared for different places and seasons, the corrections for variations from standard or average values would in each case be comparatively small and easily applied. Such a procedure would, however, complicate the matter, since it would necessitate the use of a large number of tables and would make impossible the comparison of tests at different places. It seems desirable, therefore, to select data for some place or places so located that the results shall be as nearly as possible representative of conditions in the entire region in which they will be used. So far as the United States is concerned, we now have data well suited for this purpose; and tables and curves, based upon these data and giving standard conditions, have been prepared and are discussed in the following paragraphs.

DATA USED IN THIS INVESTIGATION.

Free flight investigations are conducted at the present time almost wholly at McCook Field (Dayton), Ohio; Washington, D. C.; and Langley Field (Hampton), Va. The principal artillery testing stations or proving grounds are at Aberdeen, Md., and Dahlgren, Va. All of these places are located near (less than 3° from) latitude 40° N. It happens that of the eight stations at which observations of free-air pressure, temperature, etc., have been made by means of kites, three are situated near this same latitude, viz, Drexel (near Omaha), Nebr., latitude 41° 20′; Mount Weather, Va., latitude 39° 04′; and Royal Center, Ind., latitude 40° 53′. It has therefore seemed proper to use the data from these stations as a basis for establishing a standard atmosphere which shall best fit practical needs, so far as the United States is concerned. Accordingly, mean summer, winter, and annual temperatures for different levels up to and including 5 kilometers have been computed from those data.[2] These mean values may be accepted as representing very closely actual average temperature conditions at latitude 40°, since the values at the three stations agree well among themselves and are, moreover, based upon a large number of daily observations covering periods of from three to five years. It should be borne in mind that as the distance from latitude 40° increases, the variation from these mean values likewise increases. The variation is greatest in winter, when it amounts to about 1° C. per degree of latitude at the surface, diminishing slightly at higher levels.

For levels above 5 kilometers it has been possible to use the results of sounding balloon observations at Fort Omaha, Nebr., latitude 41° 19′, and St. Louis, Mo., latitude 38° 38′. Here again the results may be considered as representative of conditions at latitude 40°. Unfortunately, the number of observations upon which the means are based is small, but it should be remembered that smaller variations occur in the temperature gradients at great heights than at lower levels and that therefore a smaller number of observations suffices to give very satisfactory information at those levels. The observations used are those made at Fort Omaha, February 8 to March 4, 1911;[3] July 9 to 22, 1914;[4] and at St. Louis in 1904 to 1907.[5]

---

[2] For Mount Weather the data have been published in: "Mean values of free-air barometric and vapor pressures, temperatures, and densities over the United States," by W. R. Gregg. Monthly Weather Review, January, 1918, pp. 11-20. For Drexel and Royal Center see footnote 1, p. 1 of this report.

[3] Blair, Wm. R.: Sounding balloon ascensions at Indianapolis, Fort Omaha and Huron. Bulletin of the Mount Weather Observatory, vol. 4 pt. 4, pp. 183-304. 1912.

[4] Blair, Wm. R.: Free-air data by means of sounding balloons, Fort Omaha, Nebr., July, 1914. Monthly Weather Review, May, 1916, pp. 247-264.

[5] Clayton, H. H., and Fergusson, S. P.: Exploration of the air with ballons-sondes, at St. Louis. Annals of the Astronomical Observatory at Harvard College, Vol. LXVII, pt. I. 1909.

Their number and distribution are as follows:

	Altitude (meters).			
	5,000	10,000	15,000	20,000
Summer:				
Fort Omaha	17	17	14	9
St. Louis	6	5	1	0
Winter:				
Fort Omaha	21	21	17	7
St. Louis	6	2	1	0

From this table it is seen that most of the observations were obtained at Fort Omaha; those for the summer were made in the hottest month of that season and those for the winter in the latter part of that season. Hence, in each case the values are somewhat higher than true seasonal means. Thus at 5 kilometers the summer values are 3.5° C. higher than those determined from observations with kites, and in winter they are 1.5° C. higher. These differences have been adjusted by applying to the means at 5 kilometers obtained from kite observations the gradients computed from the sounding balloon records. This procedure has been followed in determining the mean temperatures at all altitudes up to the base of the stratosphere. At higher levels, up to about 20 kilometers, the mean values in both seasons are practically constant at −55° C. There may be a seasonal difference, but the records do not show it, and in any event the value of −55° C. can hardly be in error more than 2.5° C., except at 19 and 20 kilometers in summer when there is a tendency to increasing temperatures. For the present purposes it has been deemed sufficient to use the constant value, −55° C., from the base of the stratosphere up to 20 kilometers, the highest level considered.[6]

RESULTS.

Final results are shown in Figure 1 and in Table 1, values in the latter being expressed to the nearest half degree centigrade. The yearly values are the means of the two seasons, since it was found that the means for all four seasons are almost exactly the same as these.

Vapor pressure means have been determined in the same way as have the temperatures, but the computation has not been carried to heights where the values are less than half a millibar. The results are shown in Figure 2 and in Table 1, values in the latter being expressed in millibars and millimeters, to the nearest half in each case.

Barometric pressures for each level have been computed by means of the hypsometric equation, the mean temperatures of the air column for each successive altitude interval being determined from the values given in Table 1. Corrections have been made for humidity and for the variation of gravity with altitude and latitude. The results up to 5 kilometers agree closely, within 1 millibar, with the means of the actually observed values themselves. For higher levels this comparison is impossible, since the temperatures used, as already explained, are not those actually observed. The computed values of pressure for summer and winter are shown in Figure 3; the annual curve has not been drawn, but would lie midway between the other two. Values for the two seasons and for the year also are given in Table 1 and are expressed in both millibars and millimeters, to the nearest half in each case.

With the data discussed in the preceding paragraphs and presented in Table 1, it has been possible to determine corresponding air densities for each level. The values in the first column under "Density," Table 1, have been computed from the formula

$$\rho' = \frac{b - 0.378e}{T} K,$$

in which

ρ' = density expressed in percentage of standard density,
b and e = barometric and vapor pressures respectively, in millibars,
T = temperature, in °A,
and K = a constant, depending upon the conditions of pressure and temperature that are accepted as standard, in this case 1013.3 millibars, and 0° C., or K = 0.26942.

[6] It should not be inferred from this statement that a constant temperature of about −55° C. will be found at heights *above* 20 kilometers. On the other hand, the few observations thus far made, mostly in summer, show increasing temperatures with height, reaching values between −35° C. and −40° C. at 25 to 30 kilometers.

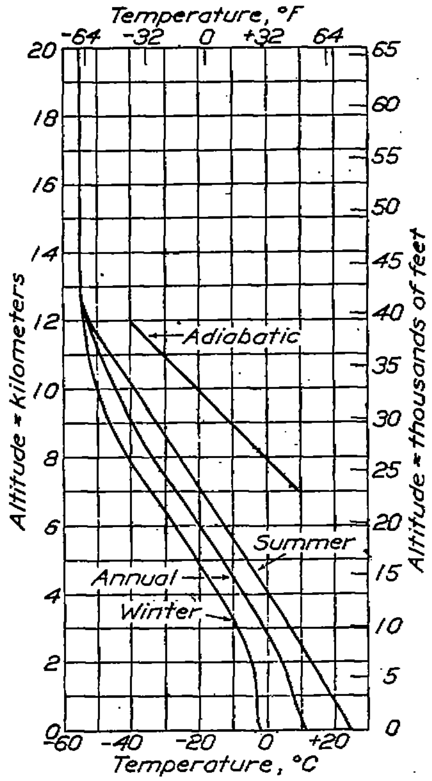

FIG. 1. Mean free-air temperatures at about latitude 40° N. in the United States.

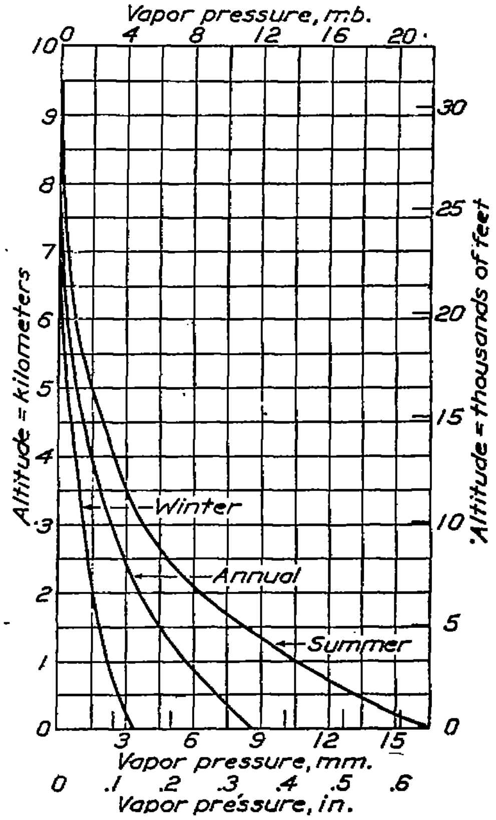

FIG. 2. Mean free-air vapor pressures at about latitude 40° N. in the United States.

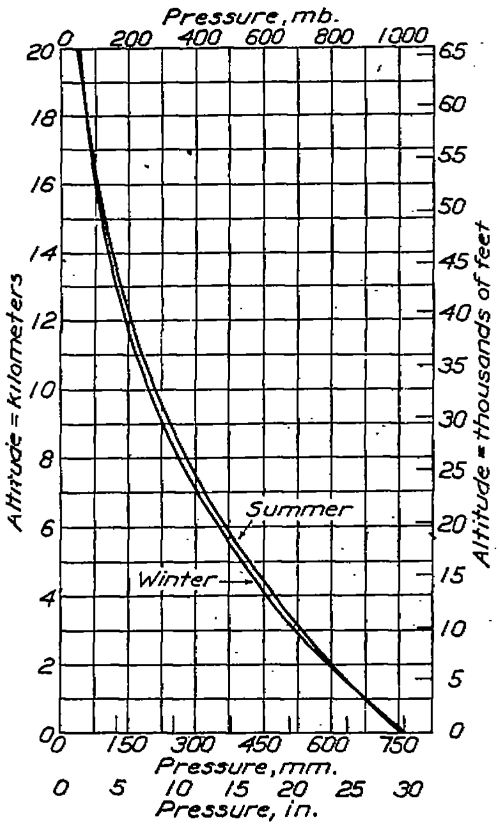

FIG. 3. Mean free-air barometric pressures at about latitude 40° N. in the United States.

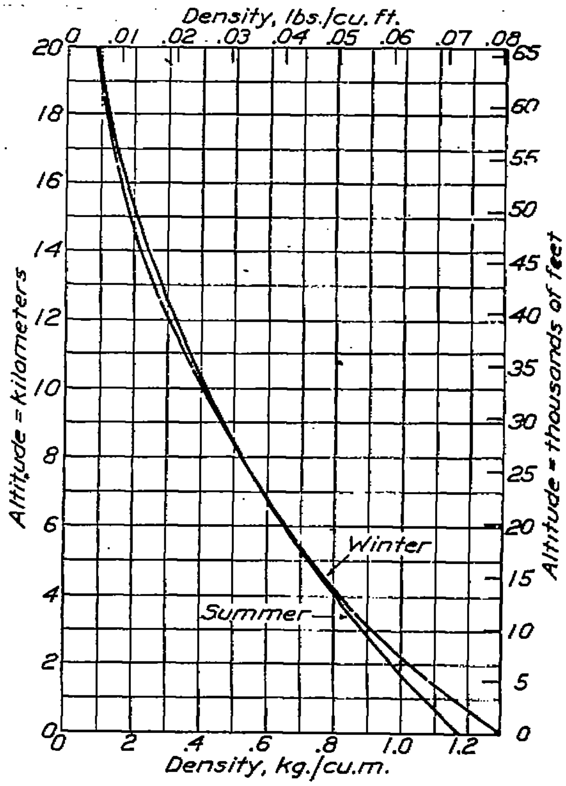

FIG. 4. Mean free-air densities at about latitude 40° N. in the United States.

The values in the second column have been obtained by multiplying those in the first by 1.293 kilograms per cubic meter, the density at 1013.3 millibars and 0° C., or $\rho = \rho' \times 1.293$. These values for the summer and winter are shown in Figure 4; the annual curve, if drawn, would lie very nearly midway between the other two.

In order to facilitate comparison with densities that have been computed for other parts of the world Table 2 has been prepared. So far as known to the writer, these are all that have been published thus far. In most cases only annual values have been given. These are presented in Table 2 in such a way that the latitudinal variation may be seen at a glance. A striking feature is the essential agreement in the density at about 8 kilometers, both in summer and winter and at all latitudes.[7]

COMPARISON WITH VALUES COMPUTED FROM TOUSSAINT'S FORMULA.

Table 2 also contains, in the last column, the values computed from Toussaint's formula. This formula has been discussed in a previous paper. (See footnote 4 in the table.) Briefly, Toussaint, using as a basis the available free-air data for Europe, has proposed the adoption, by all countries, of a "law" of linear decrease of temperature with altitude, starting at a temperature of 15° C. at sea level and attaining −50° C. at an altitude of 10,000 meters. This "law" is expressed by the formula

$$t = 15 - 0.0065Z,$$

in which

t = temperature in °C.,
and Z = altitude in meters.

Using the temperatures at various levels, as deduced from this formula, and assuming that the atmosphere is dry, and that gravity remains constant, the author has computed values of pressure and density for different heights up to 10 kilometers. The results are presented in Table 3, in which are repeated the density values given in the last column of Table 2.

Concerning these figures, Toussaint says:

> It has been found preferable to take a linear law of temperature decrease rather than to seek an equation approximate to Professor Gamba's curve, for the following reason:
>
> In order to define the standard atmosphere, what is needed is not an exact representation of that curve, but merely a law that can be conveniently applied and which is sufficiently in concordance with the means adhered to. By this method, corrections due to temperature will be as small as possible in calculations of airplane performances, and will be easy to calculate. The proposed law seems likely to realize such conditions.
>
> The deviation is of some slight importance only at altitudes below 1,000 meters, which altitudes are of little interest in aerial navigation. The simplicity of the formula largely compensates this inconvenience.
>
> It must be remarked, however, that since the isothermal layers seem to commence, in European regions, at an altitude of about 11,000 meters, it would be dangerous to extrapolate above that altitude.
>
> When it becomes an ordinary occurrence for airplanes to attain that altitude, it will be necessary to modify the law, but it suffices for the machines now in use.

Although the adopted rate of temperature decrease is arbitrary, the resulting values of density agree very well with those actually computed from European mean temperatures and pressures. Reference to Table 2 will show that the agreement with densities at latitude 40° in the United States is equally good. In fact, nowhere except at sea level does the difference equal 1 per cent, and at that level it is only 1.2 per cent. At 10 kilometers, the highest altitude for which Toussaint has computed a value, the difference is considerably less than 0.5 per cent.

In view of the close agreement above indicated and the desirability of having uniform practice in different countries it seems appropriate to recommend the adoption of Toussaint's values, *providing one set is deemed sufficient for use throughout the year*. France and Italy officially accepted them in 1920 and England has done so more recently.[8] It is to be noted, however, that Toussaint has not carried his computations above 10 kilometers. At the present time there is perhaps little need for values at higher levels, so far as aviation is concerned, but

[7] For an explanation of this, see "Level of constant air density," by W. J. Humphreys, Monthly Weather Review, May, 1921, pp. 280–281.
[8] Aeronautics. Report of the (British) Aeronautical Research Committee for the year 1920–21, p. 38.

there will almost certainly be such a need in the future. Moreover, even now the artillerist needs them. Toussaint's "law" of temperature decrease will not apply even approximately at altitudes above 11 or 12 kilometers, as clearly shown in Tables 1 and 4 and in Figure 1. It seems wise, therefore, to adopt for levels above 10 kilometers the values given in Table 2 for the United States, or else composite values, based upon the means for this country and for Europe. In either case there would be no appreciable discontinuity at 10 kilometers, since the means in both countries at that altitude are in substantial agreement with those given by Toussaint.

In the event that annual means are not considered sufficient for practical use it is recommended that the values in Table 1 for summer, winter, and the year be adopted by the United States. Additional observations in the future will hardly change these values to such an extent as to require any revision. The summer means would apply to June, July, and August; those for winter to December, January, and February; and the annual means to March, April, May, September, October, and November.

RESULTS EXPRESSED IN ENGLISH UNITS.

For the convenience of those who prefer English units, Tables 4 and 5 have been prepared. Table 4 corresponds to Table 1 and Table 5 gives English equivalents of the values computed from Toussaint's formula (Table 3). Altitudes are expressed in feet, pressures in inches, temperatures in degrees Fahrenheit, and densities in percentages of standard (dry air at 29.92 inches pressure, 32° F. and latitude 45°, =0.08071 pound per cubic foot), and in pounds per cubic foot.

LATITUDINAL VARIATION IN FREE-AIR DENSITY.

As a matter of general interest only, Table 6 has been copied from Linke's discussion of densities in all parts of the world. The means given have in large part been estimated by extrapolation and interpolation, based upon all available data. Here again is strikingly shown the substantial agreement at about 8 kilometers.

TABLE I.—*Mean free-air barometric and vapor pressures, temperatures and densities at about latitude 40° in the United States.*

Altitude, mean sea level.	Pressure.		Temperature.		Vapor pressure.		Density.	
							Per cent standard.	Kilograms per cubic meter.
SUMMER.								
m.	*mb.*	*mm.*	°*C.*	°*A.*	*mb.*	*mm.*		
0	1,014.0	760.5	25.0	298.0	22.0	16.5	90.9	1.175
500	957.5	718.0	22.0	295.0	17.5	13.0	86.8	1.123
1,000	904.0	678.0	19.0	292.0	14.0	10.5	82.9	1.072
1,500	852.5	639.5	16.0	289.0	11.0	8.5	79.1	1.023
2,000	803.5	602.5	13.0	286.0	8.5	6.5	75.4	0.975
2,500	757.0	568.0	10.0	283.0	6.5	5.0	71.8	.929
3,000	713.0	535.0	7.0	280.0	5.0	4.0	68.4	.885
4,000	630.5	473.0	0.5	273.5	3.5	2.5	62.0	.801
5,000	556.0	417.0	−6.5	267.5	2.0	1.5	55.9	.723
6,000	488.5	366.5	−12.5	260.5	1.0	1.0	50.5	.653
7,000	428.0	321.0	−19.5	253.5	0.5	0.5	45.4	.587
8,000	373.5	280.0	−26.0	247.0			40.7	.527
9,000	324.5	243.5	−32.5	240.			36.4	.470
10,000	281.0	211.0	−39.0	234.0			32.4	.418
11,000	242.5	182.0	−45.5	227.5			28.7	.371
12,000	208.5	156.5	−52.0	221.0			25.4	.329
13,000	178.5	134.0	−55.0	218.0			22.1	.285
14,000	152.5	114.5	−55.0	218.0			18.8	.244
15,000	130.5	98.0	−55.0	218.0			16.1	.209
16,000	111.5	83.5	−55.0	218.0			13.8	.178
17,000	95.5	71.5	−55.0	218.0			11.8	.153
18,000	81.5	61.0	−55.0	218.0			10.1	.130
19,000	69.5	52.0	−55.0	218.0			8.6	.111
20,000	59.5	44.5	−55.0	218.0			7.4	.095
WINTER.								
0	1,020.0	765.0	−2.0	271.0	4.5	3.5	101.2	1.309
500	957.5	718.0	−3.0	270.0	3.5	2.5	95.4	1.234
1,000	899.0	674.5	−3.0	270.0	3.0	2.5	89.6	1.159
1,500	844.0	633.0	−4.0	269.0	2.5	2.0	84.4	1.092
2,000	792.0	594.0	−5.0	268.0	2.0	1.5	79.6	1.029
2,500	743.0	557.5	−7.0	266.0	2.0	1.5	75.2	0.972
3,000	697.0	523.0	−9.0	264.0	1.5	1.0	71.0	.918
4,000	611.5	458.5	−14.5	258.5	1.0	1.0	63.7	.823
5,000	535.0	401.5	−20.5	252.5	0.5	0.5	57.1	.738
6,000	466.5	350.0	−27.5	245.5			51.2	.662
7,000	405.5	304.0	−34.5	238.5			45.8	.592
8,000	350.5	263.0	−41.0	232.0			40.7	.526
9,000	302.0	226.5	−46.5	226.5			35.9	.464
10,000	259.5	194.5	−50.0	223.0			31.4	.405
11,000	222.5	167.0	−52.5	220.5			27.2	.352
12,000	190.5	143.0	−54.0	219.0			23.4	.303
13,000	163.0	122.5	−55.0	218.0			20.1	.260
14,000	139.5	104.5	−55.0	218.0			17.2	.223
15,000	119.0	89.5	−55.0	218.0			14.7	.190
16,000	102.0	76.5	−55.0	218.0			12.6	.163
17,000	87.0	65.5	−55.0	218.0			10.8	.139
18,000	74.5	56.0	−55.0	218.0			9.2	.119
19,000	64.0	48.0	−55.0	218.0			7.9	.102
20,000	54.5	41.0	−55.0	218.0			6.7	.087
ANNUAL.[1]								
0	1,017.0	763.0	11.5	284.5	11.5	8.5	95.9	1.240
500	957.5	718.0	9.5	282.5	9.5	7.0	91.0	1.176
1,000	901.5	676.0	8.0	281.0	7.5	5.5	86.2	1.114
1,500	848.5	636.5	6.0	279.0	6.0	4.5	81.7	1.056
2,000	798.0	598.5	4.0	277.0	5.0	4.0	77.4	1.001
2,500	750.5	563.0	1.5	274.5	4.0	3.0	73.5	0.951
3,000	705.0	529.0	−1.0	272.0	3.0	2.5	69.7	.902
4,000	621.0	466.0	−7.0	266.0	2.0	1.5	62.3	.813
5,000	546.0	409.5	−13.0	260.0	1.0	1.0	55.5	.731
6,000	478.0	358.5	−20.0	253.0	0.5	0.5	50.8	.657
7,000	417.0	313.0	−27.0	246.0			45.7	.591
8,000	362.0	271.5	−33.5	239.5			40.7	.527
9,000	313.5	235.0	−39.5	233.5			36.2	.468
10,000	270.5	203.0	−44.5	228.5			31.9	.412
11,000	232.5	174.5	−49.0	224.0			28.0	.362
12,000	199.5	149.5	−53.0	220.0			24.4	.316
13,000	171.0	128.5	−55.0	218.0			21.1	.273
14,000	146.0	109.5	−55.0	218.0			18.0	.233
15,000	125.0	94.0	−55.0	218.0			15.4	.200
16,000	107.0	80.5	−55.0	218.0			13.2	.171
17,000	91.5	68.5	−55.0	218.0			11.3	.146
18,000	78.0	58.5	−55.0	218.0			9.6	.125
19,000	67.0	50.5	−55.0	218.0			8.3	.107
20,000	57.0	43.0	−55.0	218.0			7.0	.091

[1] The annual means also represent quite closely the average spring and autumn conditions.

TABLE 2.—*Mean free-air densities, kilograms per cubic meter, in different parts of the world.*

Altitude, mean sea level, meters.	SUMMER. United States, lat. 40°N.	SUMMER. Northeastern France, lat. 50°N.[1]	SUMMER. Central Europe, lat. 52°N.[2]	WINTER. United States, lat. 40°N.	WINTER. Northeastern France, lat. 50°N.[1]	WINTER. Central Europe, lat. 52°N.[2]
0	1.175	1.224	....	1.309	1.289	....
1,000	1.072	1.100	1.099	1.159	1.147	1.151
2,000	0.975	0.995	0.996	1.029	1.025	1.026
3,000	.885	.898	.898	0.918	0.920	0.920
4,000	.801	.808	.808	.823	.827	.827
5,000	.723	.727	.727	.738	.743	.743
6,000	.653	.653	.653	.662	.666	.665
7,000	.587	.587	.588	.592	.596	.593
8,000	.527	.527	.529	.526	.530	.530
9,000	.470	.472	.473	.464	.469	.466
10,000	.418	.419	.422	.405	.410	.407
11,000	.371	.369	.371	.352	.355	.351
12,000	.329	.319	.319	.303	.303	.302
13,000	.285	.274	.268	.260	.259	.255
14,000	.244	.234	.234	.223	.221	.216
15,000	.209	.201	.199	.190	.189	.186
16,000	.178	.172	.169	.163	.162	.157
17,000	.153	.148	....	.139	.138	....
18,000	.130	.127	....	.119	.118	....
19,000	.111	.109	....	.102	.101	....
20,000	.095	.093	....	.087	.086	....

Altitude, mean sea level, meters.	ANNUAL. Batavia, lat. 7° S.[3]	United States, lat. 40°N.	Canada, lat. 43°N.[3]	Europe, lat. 50°N.[3]	Southeastern England, lat. 51°N.[3]	Central Europe, lat. 52°N.[2]	Toussaint's formula.[4]
0	1.174	1.240	1.258	1.258	1.253	....	1.225
1,000	1.067	1.114	1.134	1.128	1.128	1.124	1.112
2,000	0.968	1.001	1.011	1.017	1.014	1.008	1.008
3,000	.871	0.902	0.905	0.913	0.909	0.908	0.907
4,000	.789	.813	.815	.819	.819	.816	.820
5,000	.714	.731	.733	.735	.735	.734	.735
6,000	.645	.657	.662	.661	.658	.658	.660
7,000	.581	.591	.592	.590	.589	.590	.588
8,000	.522	.527	.528	.528	.524	.528	.525
9,000	.469	.468	.470	.467	.463	.468	.467
10,000	.419	.412	.415	.411	.409	.413	.413
11,000	.374	.362	.365	.358	.355	.360	....
12,000	.331	.316	.314	.307	.305	.311	....
13,000	.294	.273	.268	.261	.261	.264	....
14,000	.261	.233	.233	.223	.223	.226	....
15,000	.225	.200	.198	.191	.191	.195	....
16,000	.191	.171	.169	.162	.162	.165	....
17,000	.162	.145	.144	.139	.139	....	....
18,000	.135	.125	.121	.119	.119	....	....
19,000	.113	.107	.102	.102	.102	....	....
20,000	.091	.091	.088	.087	.087	....	....

[1] Humphreys, W. J.: Temperatures, pressures, and densities of the atmosphere at various levels in the region of northeastern France, Monthly Weather Review, March, 1919, 47:159-161. (Based on observations at Trappes, Uccle, Strassburg, and Munich.)

[2] Linke, Franz. Über die Luftdichte. Beiträge zur Physik der freien Atmosphäre. VIII Band. Heft 2. 73-85. 1919. (Based on observations at Lindenberg, Strassburg, and Trappes.)

[3] Dines, W. H. The Characteristics of the Free Atmosphere. Geophysical Memoirs No. 13. Meteorological Office, London, 1919, M. O. 220c., p. 63.

[4] Draft of Inter-Allied Agreement on Law Adopted for the Decrease of Temperature with Increase of Altitude, March, 1920. Issued by Ministere de la Guerre, Aeronautique Militaire, Section Technique. (Discussed by W. R. Gregg in "The standard atmosphere." Monthly Weather Review, May, 1920, pp. 272-273.)

TABLE 3.—*Mean free-air barometric pressures, temperatures and densities, computed from Toussaint's formula.*

Altitude, mean sea level.	Pressure.		Temperature.		Density. Per cent standard.	Density. Kilograms per cubic meter.
m.	*mb.*	*mm.*	*° C.*	*° A.*		
0	1,013.3	760.0	15.0	288.0	94.7	1.225
500	952.0	714.0	12.0	285.0	90.1	1.165
1,000	898.0	673.5	8.5	281.5	86.0	1.112
1,500	845.5	634.0	5.0	278.0	82.0	1.060
2,000	794.5	596.0	2.0	275.0	78.0	1.008
2,500	746.5	560.0	−1.0	272.0	74.0	0.957
3,000	700.5	525.5	−4.5	268.5	70.1	.907
4,000	616.0	462.0	−11.0	262.0	63.4	.820
5,000	540.0	405.0	−17.5	255.5	56.8	.735
6,000	472.0	354.0	−24.0	249.0	51.0	.660
7,000	410.5	308.0	−30.5	242.5	45.5	.588
8,000	356.0	267.0	−37.0	236.0	40.6	.525
9,000	307.5	230.5	−43.5	229.5	36.1	.467
10,000	264.0	198.0	−50.0	223.0	31.9	.413

TABLE 4.—*Mean free-air barometric and vapor pressures, temperatures and densities, at about latitude 40° in the United States—English measures.*

Altitude, mean sea level.	Pressure.	Temperature.	Vapor pressure.	Density.	
				Per cent standard.	Pounds per cubic foot.
SUMMER.					
Feet.	*Inches.*	*°F.*	*Inches.*		
0	29.94	77.0	0.65	90.9	0.0734
1,000	28.92	73.5	.57	88.4	.0714
2,000	27.92	70.5	.50	85.9	.0694
3,000	26.95	67.0	.43	83.6	.0674
4,000	26.01	64.0	.37	81.2	.0655
5,000	25.10	60.5	.32	78.9	.0637
6,000	24.22	57.0	.27	76.7	.0619
7,000	23.35	54.0	.23	74.4	.0600
8,000	22.52	50.5	.20	72.3	.0583
9,000	21.71	47.5	.17	70.1	.0566
10,000	20.92	44.0	.15	68.0	.0549
11,000	20.16	40.5	.13	66.1	.0533
12,000	19.42	37.0	.12	64.1	.0517
13,000	18.70	33.5	.10	62.2	.0502
14,000	18.00	30.0	.09	60.3	.0487
15,000	17.32	26.5	.08	58.4	.0472
16,000	16.67	23.5	.06	56.6	.0457
17,000	16.03	20.0	.06	54.8	.0443
18,000	15.42	16.0	.05	53.2	.0429
19,000	14.82	12.0	.04	51.6	.0416
20,000	14.24	8.5	.03	49.9	.0403
21,000	13.68	4.5	.02	48.4	.0391
22,000	13.14	0.5	.02	46.9	.0378
23,000	12.62	−3.0	.01	45.4	.0366
24,000	12.11	−7.0	.01	44.0	.0355
25,000	11.61	−10.5	----------	42.5	.0343
26,000	11.14	−14.0	----------	41.1	.0331
27,000	10.68	−17.5	----------	39.7	.0320
28,000	10.23	−21.0	----------	38.3	.0309
29,000	9.80	−24.5	----------	37.0	.0299
30,000	9.39	−28.0	----------	35.7	.0288
32,000	8.60	−35.5	----------	33.3	.0269
34,000	7.87	−42.5	----------	31.0	.0250
36,000	7.19	−49.5	----------	28.8	.0232
38,000	6.56	−56.5	----------	26.7	.0216
40,000	5.97	−62.5	----------	24.7	.0199
45,000	4.71	−67.0	----------	19.7	.0159
50,000	3.71	−67.0	----------	15.5	.0125
55,000	2.92	−67.0	----------	12.2	.0099
60,000	2.30	−67.0	----------	9.6	.0078
65,000	1.81	−67.0	----------	7.6	.0061
WINTER.					
0	30.12	28.5	0.13	101.2	0.0817
1,000	28.99	27.5	.11	97.6	.0788
2,000	27.89	26.5	.10	94.1	.0760
3,000	26.84	26.5	.09	90.6	.0731
4,000	25.82	26.0	.08	87.2	.0704
5,000	24.84	24.5	.07	84.2	.0679
6,000	23.90	23.5	.06	81.2	.0655
7,000	22.99	22.0	.06	78.4	.0632
8,000	22.12	20.0	.06	75.7	.0611
9,000	21.27	17.5	.05	73.2	.0591
10,000	20.45	15.5	.04	70.6	.0570
11,000	19.66	12.5	.04	68.3	.0552
12,000	18.89	9.5	.03	66.1	.0534
13,000	18.15	6.5	.03	63.9	.0516
14,000	17.44	3.0	.02	61.9	.0500
15,000	16.74	−0.5	.02	59.9	.0483
16,000	16.07	−3.5	.01	57.9	.0467
17,000	15.42	−7.0	.01	56.0	.0452
18,000	14.80	−11.0	----------	54.2	.0437
19,000	14.19	−15.0	----------	52.4	.0423
20,000	13.60	−18.5	----------	50.6	.0409
21,000	13.03	−22.5	----------	49.0	.0395
22,000	12.48	−26.5	----------	47.3	.0382
23,000	11.96	−30.0	----------	45.8	.0369
24,000	11.44	−34.0	----------	44.2	.0356
25,000	10.95	−37.5	----------	42.6	.0344
26,000	10.47	−41.0	----------	41.1	.0332
27,000	10.01	−44.0	----------	39.6	.0319
28,000	9.57	−47.0	----------	38.1	.0308
29,000	9.14	−50.0	----------	36.7	.0296
30,000	8.73	−53.5	----------	35.2	.0284
32,000	7.96	−56.5	----------	32.4	.0262
34,000	7.25	−59.5	----------	29.8	.0240
36,000	6.60	−62.5	----------	27.3	.0220
38,000	6.01	−64.0	----------	25.0	.0201
40,000	5.46	−65.5	----------	22.8	.0184
45,000	4.31	−67.0	----------	18.0	.0146
50,000	3.39	−67.0	----------	14.2	.0115
55,000	2.67	−67.0	----------	11.2	.0090
60,000	2.11	−67.0	----------	8.8	.0071
65,000	1.66	−67.0	----------	7.0	.0056

TABLE 4.—*Mean free-air barometric and vapor pressures, temperatures and densities, at about latitude 40° in the United States—English measures*—Continued.

Altitude, mean sea level.	Pressure.	Temperature.	Vapor pressure.	Density.	
				Per cent standard.	Pounds per cubic foot.
ANNUAL.					
Feet.	*Inches.*	*°F.*	*Inches.*		
0	30.03	52.5	0.34	95.9	0.0774
1,000	28.95	50.5	.30	92.9	.0750
2,000	27.91	48.5	.27	89.9	.0726
3,000	26.90	47.0	.23	86.9	.0702
4,000	25.93	45.0	.20	84.2	.0679
5,000	24.98	42.5	.18	81.5	.0658
6,000	24.07	40.5	.16	78.9	.0637
7,000	23.18	38.0	.14	76.4	.0616
8,000	22.33	35.0	.12	74.0	.0597
9,000	21.50	32.5	.11	71.6	.0578
10,000	20.70	29.5	.09	69.4	.0560
11,000	19.92	26.5	.08	67.2	.0543
12,000	19.16	23.0	.07	65.1	.0526
13,000	18.43	20.0	.06	63.1	.0509
14,000	17.73	16.5	.05	61.1	.0493
15,000	17.04	13.0	.04	59.2	.0477
16,000	16.38	10.0	.03	57.3	.0462
17,000	15.74	6.5	.03	55.4	.0447
18,000	15.12	2.5	.02	53.7	.0434
19,000	14.51	−1.5	.01	52.0	.0420
20,000	13.93	−5.0	.01	50.3	.0406
21,000	13.37	−9.0	....	48.7	.0393
22,000	12.82	−13.0	....	47.2	.0381
23,000	12.29	−16.5	....	45.6	.0368
24,000	11.78	−20.5	....	44.1	.0356
25,000	11.29	−24.0	....	42.6	.0344
26,000	10.81	−27.5	....	41.1	.0332
27,000	10.35	−31.0	....	39.7	.0320
28,000	9.91	−34.0	....	38.2	.0309
29,000	9.48	−37.5	....	36.9	.0298
30,000	9.07	−40.5	....	35.6	.0287
32,000	8.29	−46.0	....	32.9	.0266
34,000	7.56	−51.0	....	30.4	.0245
36,000	6.90	−56.0	....	28.1	.0227
38,000	6.28	−60.5	....	25.8	.0209
40,000	5.72	−64.0	....	23.8	.0192
45,000	4.51	−67.0	....	18.9	.0152
50,000	3.55	−67.0	....	14.9	.0120
55,000	2.80	−67.0	....	11.7	.0095
60,000	2.20	−67.0	....	9.2	.0074
65,000	1.74	−67.0	....	7.3	.0059

TABLE 5.—*Mean free-air barometric pressures, temperatures and densities, computed from Toussaint's formula—English measures.*

Altitude, mean sea level.	Pressure.	Temperature	Density.	
			Per cent standard.	Pounds per cubic foot.
Feet.	*Inches.*	*°F.*		
0	29.92	59.0	94.8	0.0765
1,000	28.85	55.5	92.0	.0743
2,000	27.82	52.5	89.2	.0720
3,000	26.82	49.0	86.6	.0699
4,000	25.84	46.0	84.0	.0678
5,000	24.90	42.5	81.5	.0658
6,000	23.98	38.0	79.2	.0639
7,000	23.09	34.0	76.8	.0620
8,000	22.23	31.0	74.4	.0601
9,000	21.39	26.5	72.3	.0583
10,000	20.58	22.5	70.1	.0566
11,000	19.79	19.0	67.9	.0548
12,000	19.03	16.0	65.7	.0531
13,000	18.29	12.5	63.6	.0514
14,000	17.57	9.0	61.6	.0497
15,000	16.88	5.0	59.7	.0482
16,000	16.21	1.0	57.8	.0467
17,000	15.56	−2.5	55.9	.0451
18,000	14.93	−5.5	54.0	.0436
19,000	14.33	−9.0	52.2	.0422
20,000	13.74	−12.5	50.5	.0407
21,000	13.17	−16.5	48.8	.0394
22,000	12.63	−20.0	47.2	.0381
23,000	12.10	−24.0	45.6	.0368
24,000	11.59	−27.0	44.0	.0355
25,000	11.09	−30.5	42.5	.0343
26,000	10.62	−34.0	41.0	.0331
27,000	10.16	−37.5	39.5	.0319
28,000	9.71	−41.5	38.2	.0308
29,000	9.28	−45.0	36.8	.0297
30,000	8.87	−48.5	35.4	.0286
31,000	8.47	−52.0	34.1	.0276
32,000	8.09	−55.5	32.9	.0265
33,000	7.72	−58.5	31.6	.0255

TABLE 6.—*Mean free-air densities, kilograms per cubic meter, at various latitudes and altitudes as computed by Franz Linke.*[1]

Altitude, mean sea level.	Latitude.																			Mean.
	North.									0°	South.									
	90°	80°	70°	60°	50°	40°	30°	20°	10°		10°	20°	30°	40°	50°	60°	70°	80°	90°	
m.																				
0	1.408	1.390	1.342	1.292	1.264	1.226	1.198	1.172	1.164	1.166	1.171	1.189	1.210	1.235	1.253	1.273	1.321	1.376	1.403	1.221
4,000	0.851	0.847	0.833	0.823	0.811	0.805	0.800	0.795	0.790	0.790	0.795	0.801	0.808	0.806	0.803	0.808	0.817	0.831	0.844	0.808
8,000	.510	.515	.519	.523	.525	.528	.524	.520	.518	.518	.519	.520	.520	.526	.523	.511	.508	.504	.502	.521
12,000	.282	.288	.292	.302	.314	.324	.334	.341	.345	.345	.341	.334	.332	.323	.314	.295	.286	.280	.273	.326
16,000	.156	.158	.161	.166	.172	.182	.190	.198	.205	.208	.204	.196	.189	.181	.173	.162	.155	.155	.153	.187

[1] Über die Luftdichte. Beiträge zur Physik der freien Atmosphäre. VIII Band. Heft 3-4. 194-199, 1919.